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Mapping Canadian energy flow from primary fuel to end use

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ABSTRACT

This paper interprets the energy flow from available primary fuel to end use in all of the provinces and territories in Canada for the year 2012 using Sankey diagrams. These flow charts illustrate energy production, imports, exports, and local consumption by economic sector, and quantify the amount of useful and rejected energy. The inflow and outflow values could help determine existing energy efficiencies and energy intensity improvement potential. The total energy available in the energy flow path for all of the provinces and territories is 27,494 PJ including imports. The diagrams clearly indicate that fossil fuels dominate Canada's energy mix. Approximately 99% of the fuel in Alberta came from fossil sources in 2012 and approximately 76% of Canada's energy came from fossil sources. Alberta produced the highest amount of available energy in Canada (11,986 PJ); the lowest came from the territories (72.7 PJ). Among the non-fossil generation, hydro-electricity dominated, followed by nuclear, wind, and biomass, respectively. The overall share of thermal-based generation (fossil-fuel, nuclear, and biomass) was found to be 37.1% of Canada's produced electricity (2,222 PJ) in 2012. An analysis of rejected and useful energy indicated that the transport sector showed the poorest energy efficiency. This pictorial view of energy flow could help policy makers set targets for improving energy efficiency, select strategies for the reduction of greenhouse gases emissions, and help satisfy the vast global climate change challenges.

1. Introduction

The energy sector contributes to all socio-economic development indicators that enhance government revenues and improves lifestyles in both developing and industrialized countries. However, the energy sector also contributes to the environmental footprint in that it emits greenhouse gases (GHGs) [1]. Fossil energy is used in excess to satisfy rapid global growth [2]. Global energy sources mainly consist of solid and liquid fossils [3]. Fossil-based energy emits GHGs, which leads to global warming. Increasing the penetration of energy efficient technology could reduce GHG emissions by up to 50% by the year 2030 [4]. Increasing economic growth with less energy use and fewer GHG emissions is becoming more prevalent around the world [5]. For instance, China consumes the most energy and releases the most carbon dioxide of any country [6]. Recent work by Huang et al. [7] identifies determining factors behind China's overall energy intensity and Zhang et al. [8] identifies industrial carbon emission intensity reduction pathways. Additionally, in Denmark, primary energy demand decreased by 0.6% between 1990 and 2010 and final energy consumption increased by 4.9% due to the implementation of energy efficiency improvement programs [9]. A detailed understanding of energy demand and supply flow is required in order to design and implement such a program. Therefore, it is important to study energy flows in different ways and different sectors in a system.

Canada has the largest hydrocarbon base in North America and is at the upper ranking of energy production and exports irrespective to all types of energy. For example, crude oils and natural gas are 5th and 4th, respectively, in production and export in the world market; uranium is 2nd both in production and export in the world market; and hydro-electricity and biofuel are 3rd and 5th, respectively, in production in the world [10]. Canada has allocated $195 million under the ecoENERGY Efficiency program over five years [11]. In Canada, energy consumption increased by about 23% over the last two decades [12]. Canada's energy expenditure is largely in the residential, commercial, and industrial sectors. About $152 billion was spent on energy to operate heating and cooling devices, appliances, cars, and industrial processes in 2009. This is equivalent to about 11% of the country's GDP [13].

Canada has a complex energy flow. Energy production, local consumption, and inter-provincial and international exports and imports are common in Canada. The residential, commercial and institutional, industrial, transportation and agriculture sectors are all energy demand sectors. Canada's energy consumption in 2012 was 8735 PJ. The industrial sector consumed the largest share of end use energy (38.38%), followed by transport (29.65%), residential (16.70%), commercial and institutional (12.24%), and agriculture (3.03%). The energy used by

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Nomenclature

BC	British Columbia
GHG	greenhouse gas
GDP	gross domestic product
CO_2	carbon dioxide
PJ	petajoule
HVAC	heating, ventilation and air conditioning
U.S.	United States
U.K.	United Kingdom
CANSIM	Canadian socio-economic information management
CHP	combined heat and power
NGL	natural gas liquids
NG	natural gas
NFL	Newfoundland and Labrador
NS	Nova Scotia
NB	New Brunswick
PEI	Prince Edward Island

these five sectors emitted 473.4 million tonnes (CO_2 equivalent) of GHGs in 2012 [12], of a total 699 million tonnes (CO_2 equivalent) that year [10]. The total fossil fuel production was 16,459 PJ in 2012; the major forms of fossil fuels are crude oil (47.6%) and natural gas (38.7%). Coal and natural gas liquids contributed 9.6% and 4.0%, respectively, of the fossil fuel supply in 2012. As energy consumption increases, GHG emissions from fossil fuel production have also increased and went up by 10% between 2005 and 2012 [10]. Net GHG emissions increased by 36%, 29%, and 8% in the transportation, commercial/institutional, and industrial sectors, respectively, between 2005 and 2009 [13].

In December 2015, Canada committed to the Paris Agreement, which included a commitment to restrict the global average temperature increase to below 2 °C over pre-industrial levels. This is a significant challenge in and of itself, and its complexity is compounded by Canada's massive economic growth, which is projected to be approximately 32% higher in 2020 than it was in 2005 [14]. In order to meet these commitments by the target dates, Canada must consider the rational use of energy in a timely manner, especially as the energy sector is a key part of Canada's economy. Energy use in Canada has become more efficient over time, but energy consumption has simultaneously increased. Hence, it is necessary to understand energy flow from primary fuel to end use in different sectors.

Canada is composed of 13 regions: 10 provinces and 3 territories. A map of Canada with its regions is shown in Fig. 1. Each region has an independent and unique energy system that is explored in this paper. Table 1 compares the population and GDP for each region in 2012. Ontario and Quebec are the most populous provinces in Canada with 38.6% and 23.3% of the national population, respectively. Ontario and Quebec are also the most economically active with 39% and 17% of the 2012 national GDP, respectively. The eastern provinces Newfoundland and Labrador (NFL), Prince Edward Island (PEI), Nova Scotia (NS), and New Brunswick (NB) make up Atlantic Canada. The combined population and GDP of the Atlantic provinces contributed 6.8% and 5.7% to the Canadian total in 2012, respectively. The western provinces British Columbia (BC), Alberta, and Saskatchewan have the largest GDP/

Fig. 1. Provincial and territorial map of Canada (contains information licensed under the Open Government License – Canada) [17].

Table 1
2012 population and GDP of the provinces and territories of Canada.

	Population (thousands) [18]	GDP (million $2007 CAD) [19]	Thousand $GDP per person
Canada	34,750.5	1,668,524	48.0
Newfoundland and Labrador	526.5	26,719	50.7
Prince Edward Island	145.1	4,952	34.1
Nova Scotia	944.9	35,567	37.6
New Brunswick	756.8	28,417	37.5
Quebec	8,085.9	324,993	40.2
Ontario	13,413.7	622,717	46.4
Manitoba	1,250.3	55,674	44.5
Saskatchewan	1,086	58,514	53.9
Alberta	3,880.8	290,544	74.9
British Columbia	4,546.3	211,427	46.5
Yukon	36.1	2,407	66.7
Northwest Territories	43.6	3,511	80.5
Nunavut	34.7	1,784	51.4

capita. This is largely due to significant fossil resource reserves and exploitation, including the oil sands in Alberta [15,16]. The Yukon, Northwest Territories, and Nunavut make up the Territories of Canada. The Territories do not have significant population or GDP (less than 0.5% of the Canadian total for both) due to the Arctic conditions of northern Canada.

Sankey diagrams are a widely used flow-pattern visualization tool that use arrows to illustrate a process; the width of the arrow and lines indicates the energy intensity of a particular process [20]. The diagrams show energy flow from primary sources to end uses through different processes and consumptions in different economic sectors. Several tools are described in the literature for the flow process visualization. Graveland describes the flow of different material, energy, exergy, and chemical processes using a tool called Exan™ Pro [21]. Another report describes the conversion of 2-D Sankey diagrams into 3-D diagrams for energy-efficient product development in mechanical engineering with virtual reality tools [22]. Szargut et al. use a band diagram for energy and exergy flow of thermal, chemical, and metallurgical processes [23]. Visualization tools are used to present global energy flow processes and efficiencies at different stages of energy conversion for planning and implementing measures to lower GHG emissions. Ma et al. did an evaluation and validation study using Sankey diagrams for energy flow from primary source to end use in China [24]. From the publications cited above, we can observe that Sankey diagrams facilitate the selection of energy-efficient scenarios of energy flow. Cullen and Allwood described a global map of energy conversion efficiency through a Sankey diagram for the reduction of GHG emissions [25]. Suzanne et al. described the use of a Sankey diagram to show annual consumption of electricity and natural gas and other end-use energy for a building hub. Through Sankey diagrams, the researchers easily identified large sources of end-use consumption with seasonal variations for different sectors [26]. These studies describe the evolution of mapping global energy with the help of Sankey diagrams. The diagrams can also be used to analyze energy flow in order to predict future scenarios. Lombard et al. used a Sankey diagram to analyze energy flow for heating, ventilation, and air conditioning (HVAC) and found that HVAC systems were responsible for approximately 50% of a building's total energy consumption and identified areas for efficiency improvement [27]. The diagrams also illustrate energy transformations in thermal comfort services (i.e., heating and cooling). Efficiency improvements should be focused on those areas of energy flow that have the highest potential for energy savings and GHG emissions mitigation. These can be calculated in the energy flow chains of a Sankey diagram. System energy loss can also be shown in Sankey diagrams [25,28].

Further examples of Sankey diagram use to map energy pathways are the mapping of energy use in the U.S. [29], a GHG emissions flow diagram [30], global energy flows from primary energy through carriers to end uses and losses for the year 2004 [31], global exergy and carbon flow diagrams [32], U.S. energy flow process diagrams done in 2014 [33], an energy flow diagram of the U.K. in 2010 [34], and energy flow diagrams for China [24].

As energy production, distribution, and consumption are complex, a Sankey diagram is an appropriate tool for analyzing energy flow. An earlier study investigated energy flows for Alberta's energy sector, one of the provinces in Canada [1]. Little has been reported on end use and rejected energy in Canada's economic sectors. The overall objective of the paper is to develop a complete map of energy flow patterns using Sankey diagrams in different Canadian provinces as well as a gross energy flow of Canada as a whole. The main objective of this study is to address energy flow from primary fuel to end use as well as the useful and rejected energy through the various energy transformation and end-use processes in different sectors in Canada. There are different inter-provincial export-imports as well as international export-imports, all of which will be discussed in this paper.

2. Methodology

2.1. Energy database

Canada's energy flow was mapped using energy-mix data. Energy data for coal, crude oil, natural gas, natural gas liquids, hydro, nuclear, biomass, etc., were used to analyze flow processes. Energy from import sources was also included in the synthesis. The energy data, available up to 2012, were collected from the Government of Alberta, Natural Resources Canada, the Canadian socio-economic information management (CANSIM) database, and the World Nuclear Association [10–13,35,36].

2.2. Sectoral energy analysis

Energy demand in the residential, commercial and institutional, industrial, transport, and agriculture sectors was analyzed in this study. Energy input, used energy, and waste energy in the economic sectors were analyzed and quantified. Energy from fossil sources (coal, crude oil, natural gas, and natural gas liquids), renewable sources (hydroelectricity, biomass, wind, and solar), nuclear sources, and imports were critically synthesized and plotted on Sankey diagrams to indicate the flow processes.

2.3. Developing Sankey diagrams

Sankey diagrams are flow diagrams in which the width of the lines indicates the quantity of flow. In this study, these diagrams are used to illustrate energy flow processes from primary fuel to end use. The diagrams help us understand specific energy flows in each economic demand and supply sector as well as distribution of energy with respect to different processes. In this study, we estimate energy distribution through the various stages of energy flow, identify major energy flows in various economic sectors, and illustrate total useful energy and energy loss. Though some very recent data are available in some sectors (up to 2015), 2012 data are fully available and used in this study to allow for a comprehensive sector-wide annual study. All emerging small-quantity energy sources such as wind, solar, and biomass are included in the diagrams. The main two sources of inflow energy in Canada are indigenous production and imports. Energy outflow is through local consumption, non-energy use (of NG, NGLs, and petroleum products), and exports. The gross flow of the Canadian energy pool is shown in Fig. 2. Energy resource sectors are clearly identified by category and type of energy. Stock in supply sources is maintained by indigenous production and import from and export to provinces and the U.S. Primary fuel includes coal, crude oil, natural gas, natural gas liquids, and biomass. Electricity comes mainly from hydro, nuclear, coal,

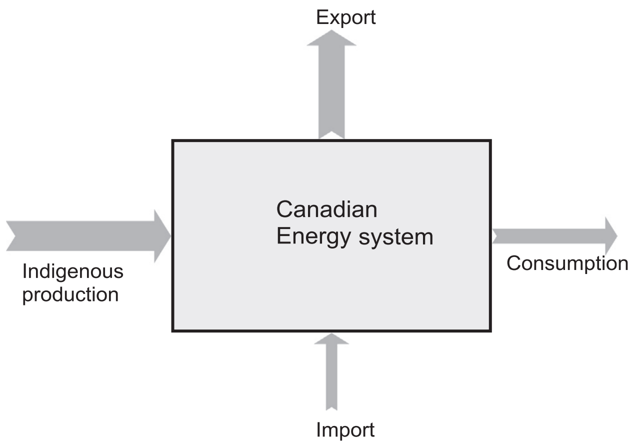

Fig. 2. Canada's gross energy flow.

and natural gas. Supply sources are listed in Table 2. Any data sources where mass or volume was given were converted to energy using 2012 energy conversion factors [37]. The energy demand sectors are Canada's five economic sectors: residential, commercial and institutional, industrial, transport, and agriculture. The end-use sub-categories of the demand sectors are: space heating and cooling, lighting, running appliances, industrial and mining processes, and passenger and freight transport (Table 3).

The map of energy flows from source to end use is given in Fig. 3. The main energy sources include nuclear, hydro, coal, crude oil, natural gas and gas liquids, and others. These are derived from net indigenous production, net import, and stock variation. Electricity is the main secondary energy carrier. Most electricity comes from hydro, nuclear power, biomass, and coal power plants. Electricity export and import are also included in the map. The data for the energy sources are mainly derived from Natural Resources Canada's (NRCan) energy use database, StatsCan's Canada Yearbook, and CANSIM's database, all for 2012 [36,48,49] (as listed in Table 2). Rejected and useful energy in each sector was calculated based on ratios reported by Kaiper in 2003 [50] (Table 4).

The software tool e!Sankey pro 3.2 was used to generate the Sankey diagrams for this study [51]. The energy flow for the provinces and territories as well as all of Canada is illustrated in Sankey diagrams and discussed in the results and discussion section. The energy available to each energy source module was calculated as shown in Eq. (1). The outflow of the energy was balanced as shown in Eq. (2). Summation of flows may not be exactly equal to displayed totals due to rounding.

$$\text{Energy available} = \text{Production} + \text{Imports} + \text{Stock changes} - \text{Losses} \tag{1}$$

$$\text{Outflow energy} = \text{Energy demand} + \text{Non energy use} + \text{Export} \tag{2}$$

3. Results and discussion

3.1. Energy flows in different Canadian provinces and territories

3.1.1. Energy flow in Alberta in 2012

Alberta's total energy flow in 2012 is illustrated in Fig. 4. Alberta's total energy supply including electricity imports was 11,986 PJ in 2012. Of this total, almost 99% came from fossil sources and the remaining 1% came from hydro, wind, and biomass. Among the fossil fuels, crude oil contributes the most energy (53.3%) followed by natural gas (36.6%), coal (5.3%), and natural gas liquids (NGLs) (4%). Crude oil production has increased by 35% since 2009 [38]. Electricity generated in Alberta's energy mix was an estimated 252 PJ [39,46], which is 5.4% more than the electricity generated in 2009 [1]. About 93% of electricity available was from fossil fuel sources. A significant amount of coal (445 PJ) was consumed to generate electricity [45]. In Alberta electricity is generated from coal and natural gas (NG). During the study year, total electricity consumption in Alberta was 266 PJ. To meet the demand, 26 PJ of electricity were imported. This suggests that electricity generation lags behind demand.

Alberta produces a large amount of fossil-based fuel, more than is consumed, and a significant amount of this fuel is exported. Crude oil exports were the highest (4905 PJ) followed by NG (2602 PJ) and NGLs (163 PJ). Total primary and secondary energy exports have increased by 44% since 2009 in Alberta [38]. Non-energy use of fossil fuel is seen mostly in crude products (234 PJ) and NGLs (222 PJ). On the demand

Table 2
Canada's energy supply sector.

Source category	Source sub-category	Description
Supply source	Natural resource	Value represents gross disposition of the commodity
	Import [36,38]	Primary and secondary energy imported to Canada. Regional imports show imports from foreign sources plus net regional transfers. Where data was not available, estimates were calculated based on historical values
	Export [35,36,38]	Primary and secondary energy exported from Canada. Regional exports show exports to a foreign destination plus net regional transfers. Where data was not available, estimates were calculated based on historical values
Primary source	Coke and coke oven gas [12,38]	Energy transformed from coal
	Nuclear [35,38]	Electricity from nuclear power
	Hydro [38,39]	Electricity from hydro-power, includes tidal
	Wind [38,39]	Electricity from wind power
	Solar [38,39]	Electricity from solar power
	Biomass [12,38,40]	Combustible wood forest/agriculture residues, biofuel. Does not include spent pulping liquor for electricity generation in regional diagrams
	Coal [12,41]	Bituminous, sub-bituminous, lignite coal. Includes coke for the Canada diagram only
	Crude oil [38,42]	Bitumen, light crude oil, medium crude oil, heavy crude oil, pentanes plus, condensate, synthetic crude oil (SCO), petroleum products. Crude oil sold to non-refinery customers is included in the totals
	Oil products [12,38]	Crude oil is converted into petroleum products including gasoline, diesel, still gas, liquefied petroleum gases (LPGs), kerosene and stove oil, light and heavy fuel oils, petroleum coke, aviation fuels, and non-energy products. All petroleum products are shown to flow through the oil products module, even if no refining exists in a region
	Natural gas [12,38,43]	Natural gas, coal bed methane
	Natural gas liquids [38,44]	Propane, butane, and ethane
	Electricity [38]	The value in the module represents electrical energy disposition including producer consumption and grid losses
Energy carrier	Fuel [12,36,38]	Oil, gas, coal, biofuel used for engines, boilers, burners
	Electricity [12,45,46]	Electricity generation from power plants including combined heat and power (CHP), nuclear, hydro, and other renewables
	Non-energy use [44,47]	Industrial used materials from petroleum sources, natural gas, and natural gas liquids

Table 3
Energy demand side sectors in Canada.

Economic sectors	Description
Residential [12,38]	Energy demand for space heating and cooling, water heating, appliances, and lighting. Energy comes from both primary and secondary sources
Commercial and institutional [12,38]	Energy demand for space heating and cooling, water heating, space lighting, street lighting, and other
Industry [12,38]	Energy demand for mining, pulp and paper, production and processing of chemicals and metals, manufacturing, construction, pipeline, and forestry. Includes producer consumption and steam generation
Transport [12,38]	Energy demand for passenger, freight, and off-road transportation by road, air, rail, and marine
Agriculture [12,38]	Motive and non-motive energy demand for agricultural purposes

side, 2645 PJ of energy were consumed. Among the economic demand sectors, the industry sub-sector consumed the most energy (66%), followed by transport (16.3%), residential (8.2%), commercial (7.5%), and agriculture (2.1%) [12,40–44,52]. Natural gas consumption in the industrial sector was 1139 PJ in 2012, a 51% growth since 2009 [38]. The overall ratio of rejected energy to useful energy is estimated to be 1:1.42. The total import of energy was 67 PJ, whereas the total export was 8244 PJ. This shows that there was a surplus in energy production in Alberta in 2012.

3.1.2. Energy flow in the Atlantic (Newfoundland and Labrador, Nova Scotia, New Brunswick, Prince Edward Island) in 2012

The total energy flow for the Atlantic provinces in 2012 is illustrated in Fig. 5. 1946 PJ of energy were available in the energy flow mix in the Atlantic provinces in that year, of which about 1118 PJ were imported. Large shares of available energy came from crude oil (1424 PJ). About 72% of the Atlantic's crude oil energy was exported. This is a 62% decrease since 2009 and corresponds with a 42% decline in crude production from 2009 to 2012 [38]. Of the electricity available, the mix comprised nuclear, hydro, wind, coal, and imports for a total of 228 PJ. Of this total, 236 PJ [39,46] was generated within the Atlantic provinces in 2012; this figure is 3.5% more than the amount generated in 2009 [46]. Hydro-power dominated the electricity mix share with 46% of the total. About 29% of the electricity was exported during the study year. There appears to be an abundance of electricity in these provinces. Total energy supply disposition to different economic sectors was estimated to be 604 PJ. The industrial sector consumed the highest demand share (35.9%), followed by the transport (31.9%), residential (19.4%), commercial and institutional (11.1%), and agriculture sectors (1.7%) [12,40–44,52]. The overall ratio of rejected energy to useful energy is estimated to be 1:0.98. The total export of energy (1152 PJ) was higher than the imports, indicating there was surplus energy production in the Atlantic provinces in 2012.

3.1.3. Energy flow in British Columbia in 2012

The total energy flow for British Columbia in 2012 is illustrated in Fig. 6. Total available energy in British Columbia's energy mix is estimated to be 3055 PJ in 2012. Of the total available energy, 86% came from fossil sources and the rest from renewable sources. Among the fossil fuels, natural gas provided the largest share (45%) of the total energy mix followed by coal (25.7%), crude oil (13.7%), and NGLs (1.6%). The total amount of electricity available in the province was 290 PJ [39,46]. Of this total, 265 PJ were generated in the province; this is 13.25% more than the amount generated in 2009 [46]. Electricity came mainly from hydro (80.2% of the total electricity mix) and the rest from imports (9.9%) and other sources (wind and biomass). Approximately 19% of the total electricity was exported. Electricity imports to BC have decreased by 33% since 2009 [38]. Coal was not used in the provincial energy mix; all of the province's coal is exported. Crude oil production was not enough to meet the demand; therefore, more was imported. Natural gas is abundant in the province; about 73.5% (1011 PJ) of the natural gas was exported. The production of natural gas has increased by 23% between 2009 and 2012 [38]. In the demand sectors, 1008 PJ of energy were consumed. Of the total consumption, the industrial sector consumed the highest amount of energy (44.3%) in the province followed by the transport sector (29.9%), the residential sector (14.6%), the commercial sector (9.4%), and the agriculture sector (1.8%) [12,40–44,52]. The ratio of rejected and useful energy is estimated to be 1:1.55. Total imported energy was 401 PJ, whereas total exported energy was 1891 PJ. This demonstrates a surplus in energy production in the province in 2012.

Table 4
Rejected and useful energy ratios [50].

Economic sectors	Useful/rejected energy ratio
Residential	0.75
Commercial and institutional	0.75
Industry	0.80
Transport	0.20
Agriculture	0.80

3.1.4. Energy flow in Manitoba in 2012

The total energy flow for Manitoba in 2012 is illustrated in Fig. 7. Total available energy in Manitoba's energy mix was 1022 PJ in 2012. Of the total energy available, 55.6% came from natural gas followed by crude oil (27.9%), hydro-electricity (11.3%), NGLs (2.2%), and the rest from biomass, wind, and coal. A large amount of natural gas (550 PJ) is transferred through the province for international export. Crude oil production increased 119% between 2009 and 2012, driving a 94% increase in crude oil exports during the same period [38]. Almost all the

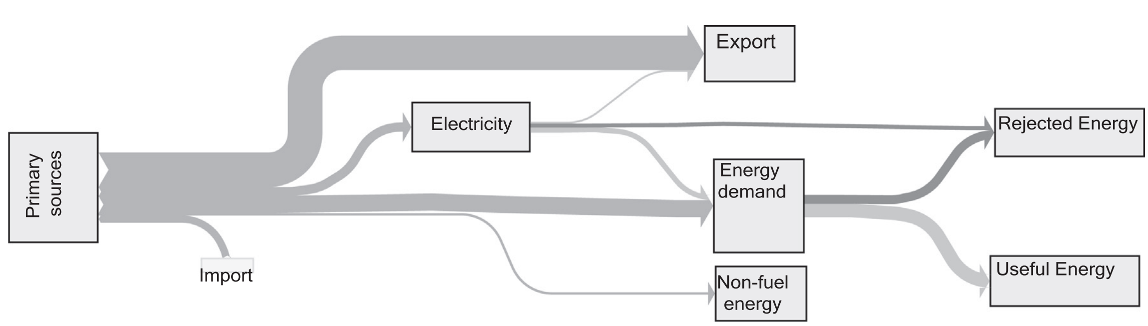

Fig. 3. Sankey diagram showing energy flow from source to end use.

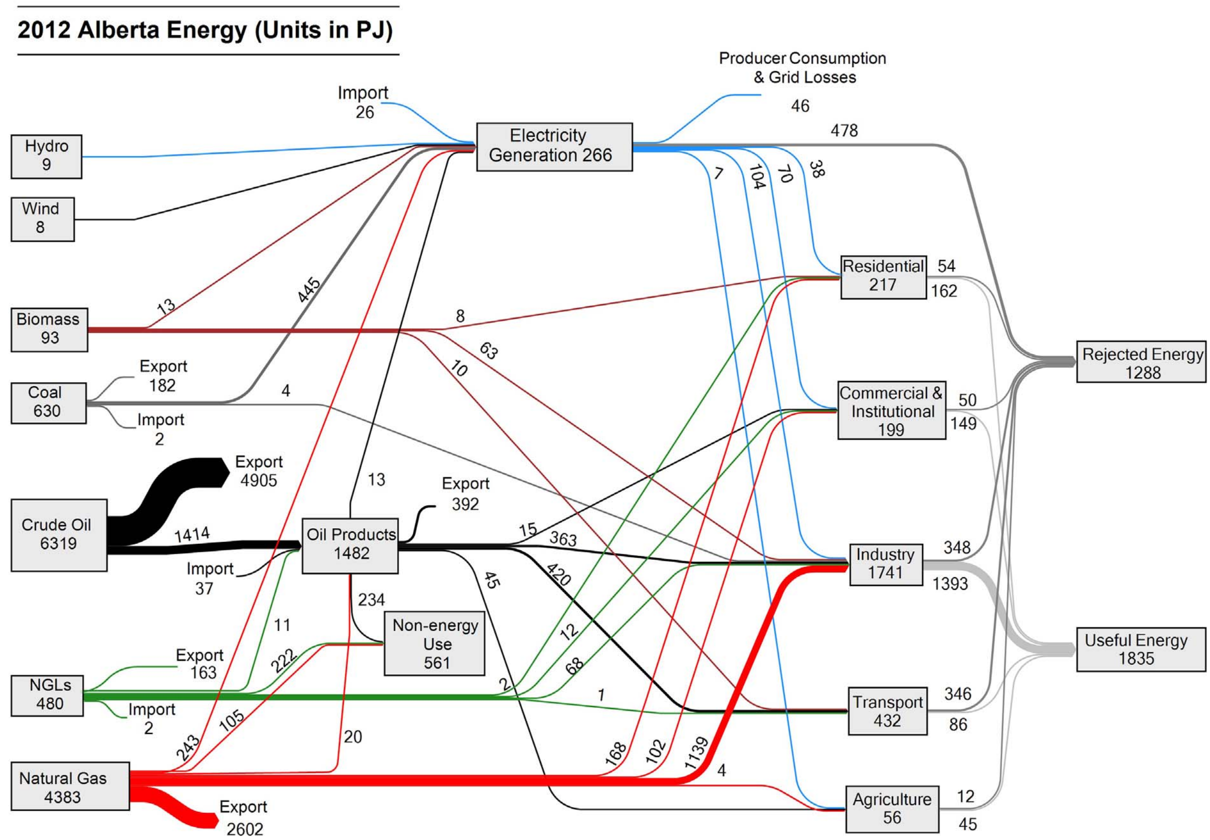

Fig. 4. Sankey diagram showing energy flow for Alberta in 2012.

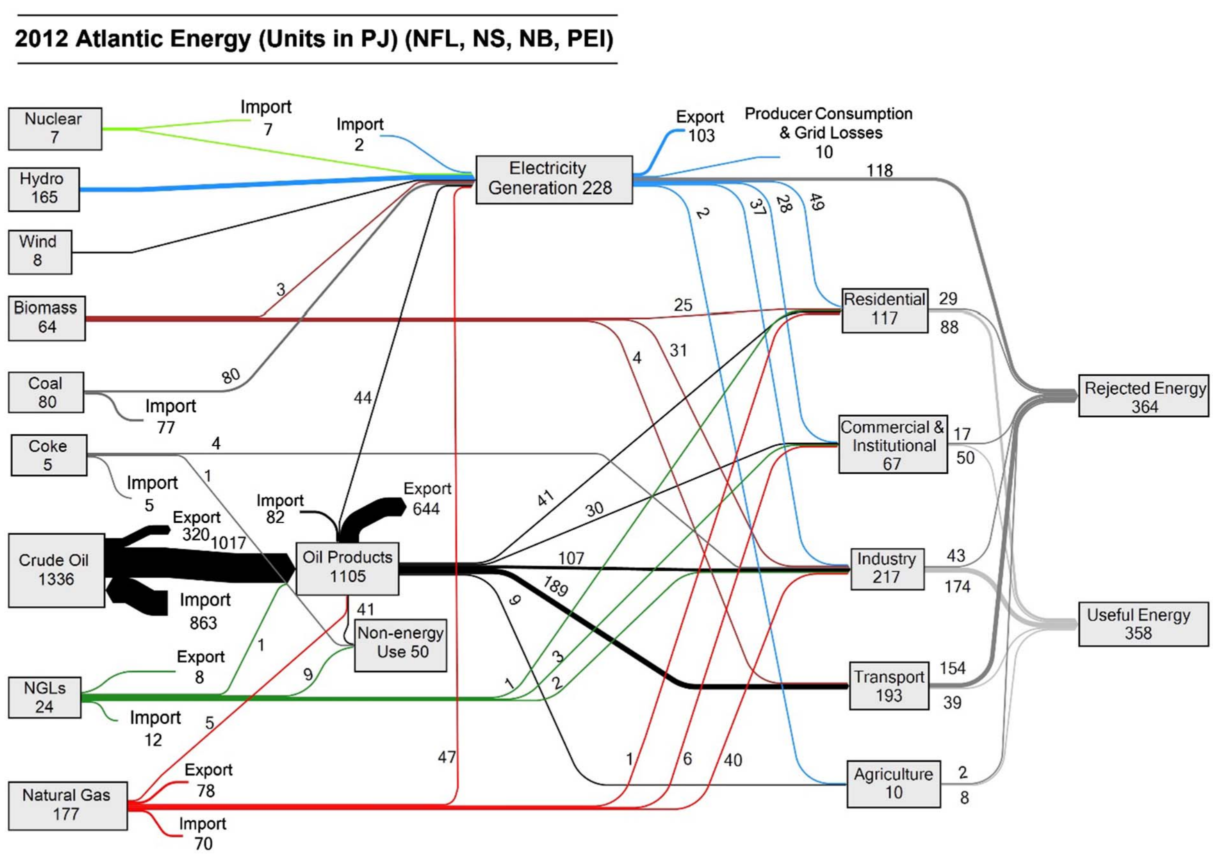

Fig. 5. Sankey diagram showing energy flow for the Atlantic provinces in 2012.

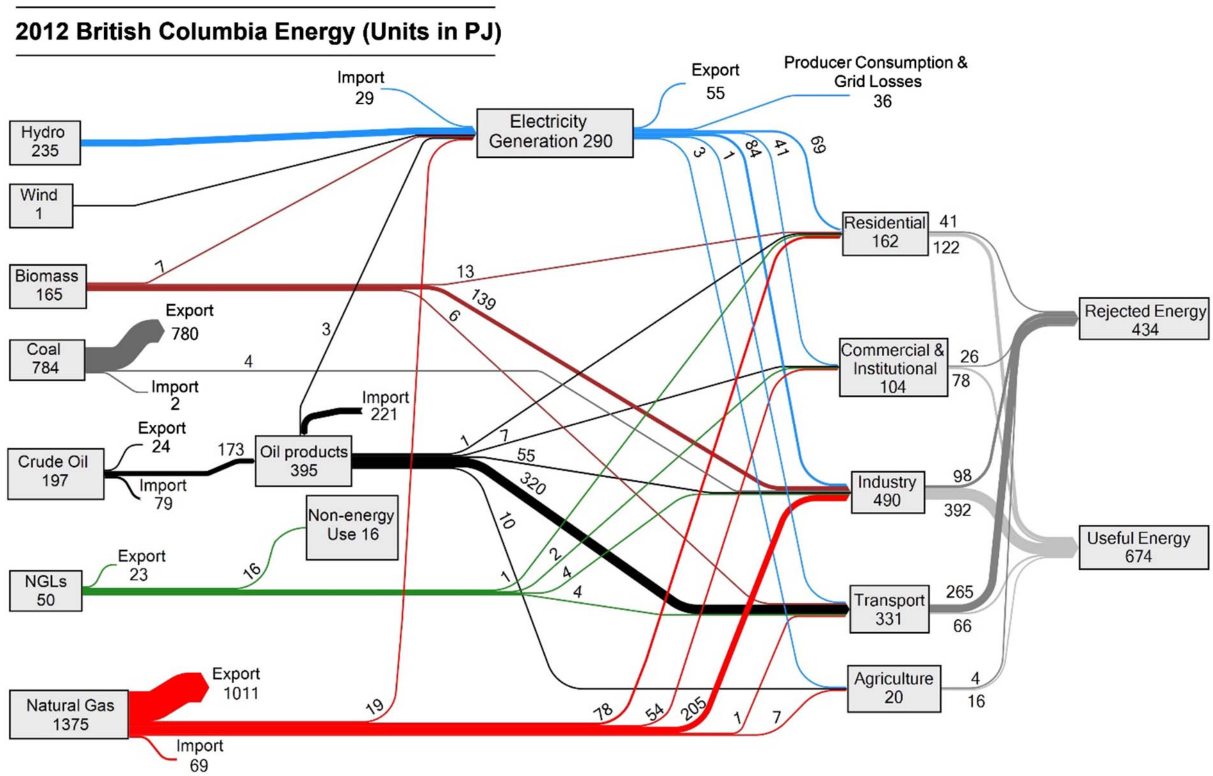

Fig. 6. Sankey diagram of energy flow for British Columbia in 2012.

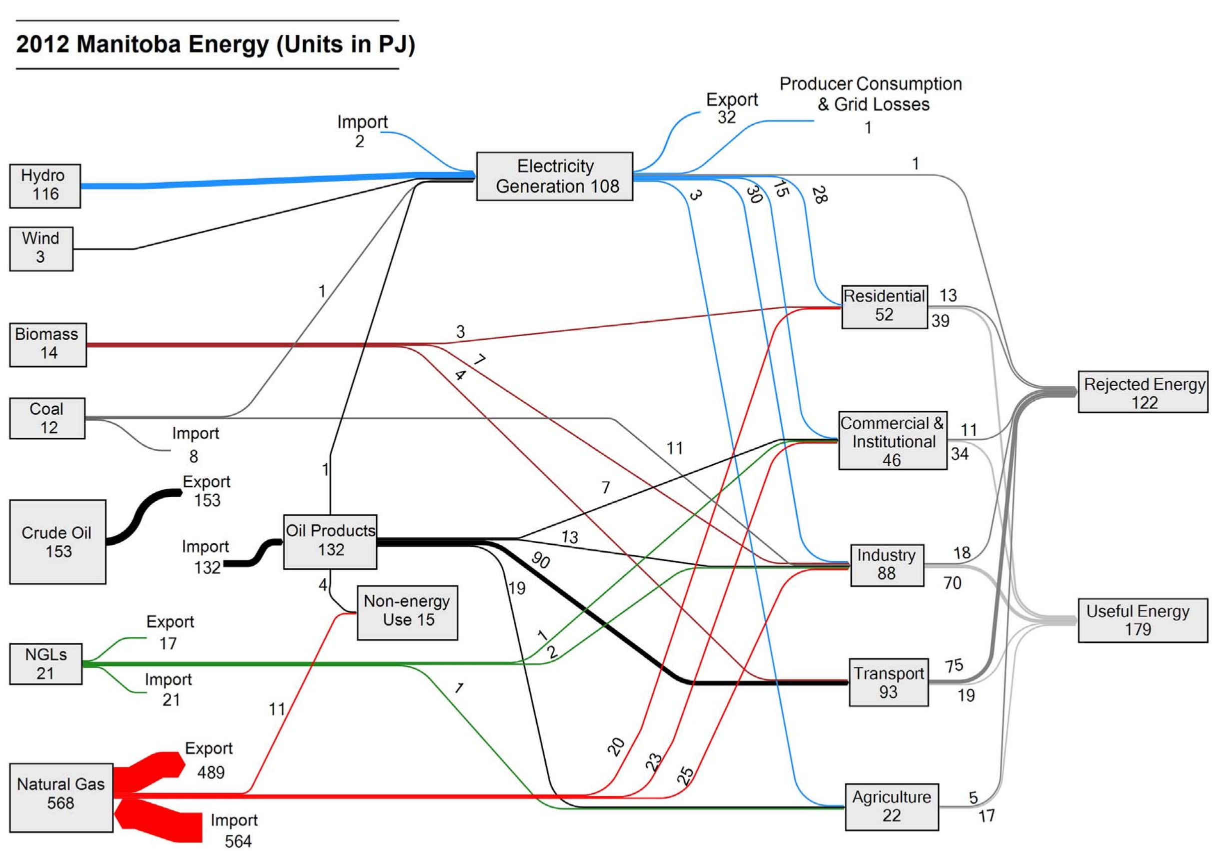

Fig. 7. Sankey diagram showing energy flow for Manitoba in 2012.

electricity in 2012 came from hydro-power plants; some came from imports and other sources. Of the total electricity, 119 PJ [39,46] came from in-province generation; this figure is 2.4% lower than the amount generated in 2009 [46]. Generation was 119 PJ; however, only 108 PJ of electricity was recorded in the power mix. About 26% of the total pooled electricity was exported in 2012. In the demand sectors, 300 PJ of energy were consumed in 2012. Of the total energy demand, the highest amount of energy was consumed in the transport sector (31.1%), followed by the industrial sector (29.3%), the residential sector (17.2%), the commercial and institutional sector (15.2%), and the agriculture sector (7.2%) [12,40–44,52]. The ratio of rejected and useful energy is estimated to be 1:1.47. The total amount of energy imported was 727 PJ, whereas the total exported was 690 PJ, resulting in 37 PJ net imports. This demonstrates a deficit in energy production in the province in 2012. Primary energy imports grew by 422% between 2009 and 2012 [38].

3.1.5. Energy flow in Ontario in 2012

The total energy flow for Ontario in 2012 is illustrated in Fig. 8. The total available energy in Ontario's energy mix in 2012 was 7909 PJ. The energy mix in Ontario is exceptional in that all types of energy are present in the mix. Ontario imported all of Saskatchewan's nuclear energy (4500 PJ) and processed it. 692 PJ of nuclear energy were used to produce electricity, and the remainder was exported. The total electricity in the pool was 559 PJ in 2012 [39,46]. Of this total, 552 PJ came from in-province generation; this figure is 4.3% higher than the electricity generated in 2009 [46]. The province has a significant amount of hydro- (122 PJ) and wind- (14 PJ) generated electricity and generated 1 PJ of solar electricity in 2012. Ontario is the only province with a significant level of solar power production in the study year. The fossil fuel resource availabilities are crude oil (1135 PJ), NG (1336 PJ), NGLs (244 PJ), and coal (168 PJ). Crude oil and natural gas were mostly from imported sources with little coming from provincial production. Crude oil imports decreased by 75% and natural gas imports increased by 95% from 2009 quantities [38]. Energy from crude oil contributed most of the province's internal energy flow-mix (1410 PJ) followed by NG (1026 PJ), nuclear (692 PJ), NGLs (166 PJ), biomass (143 PJ), hydro (122 PJ), and wind and solar. The share of non-energy fossil energy use was 343 PJ and came mainly from crude oil and NGLs. Electricity in this province was provided from eight different in-province fuel sources as well as imported electricity. The major share of electricity came from nuclear; other sources are hydro, NG, coal, biomass, wind, and solar. In the demand sector, 2647 PJ of energy were consumed in 2012. Of the total energy demand, the transport sector scored the highest consumption rate (32.6%) followed by the industrial sector (29.5), the residential sector (21.1%), the commercial and institutional sector (14.5%), and the agriculture sector (2.3%) [12,40–44,52]. The ratio of rejected and useful energy is calculated to be 1:0.93. Total imports of energy were 7061 PJ, whereas total exports were 4331 PJ. This indicates a deficit in energy production for the province in 2012.

3.1.6. Energy flow in Quebec in 2012

The total energy flow for Quebec in 2012 is illustrated in Fig. 9. The total available energy in Quebec's energy mix was 2409 PJ in 2012. The total electricity pool in the province was 754 PJ, out of which 716 PJ came from in-province generation [39,46]. This is 1.3% more than the electricity generated in 2009 [46]. The province is rich in hydro-electricity and produced 691 PJ in 2012, half the amount produced nationally. Most of the fossil fuel used in Quebec was imported during the

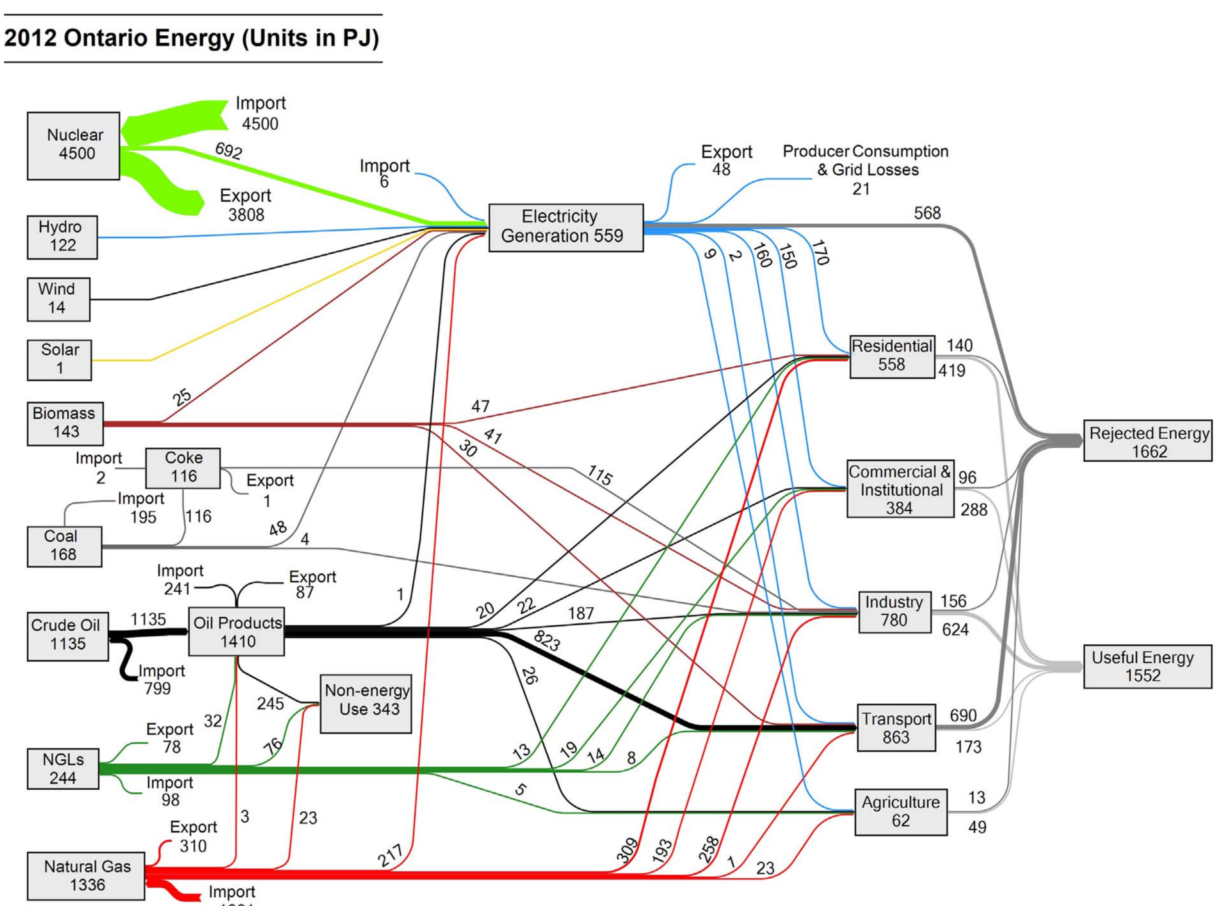

Fig. 8. Sankey diagram showing energy flow for Ontario in 2012.

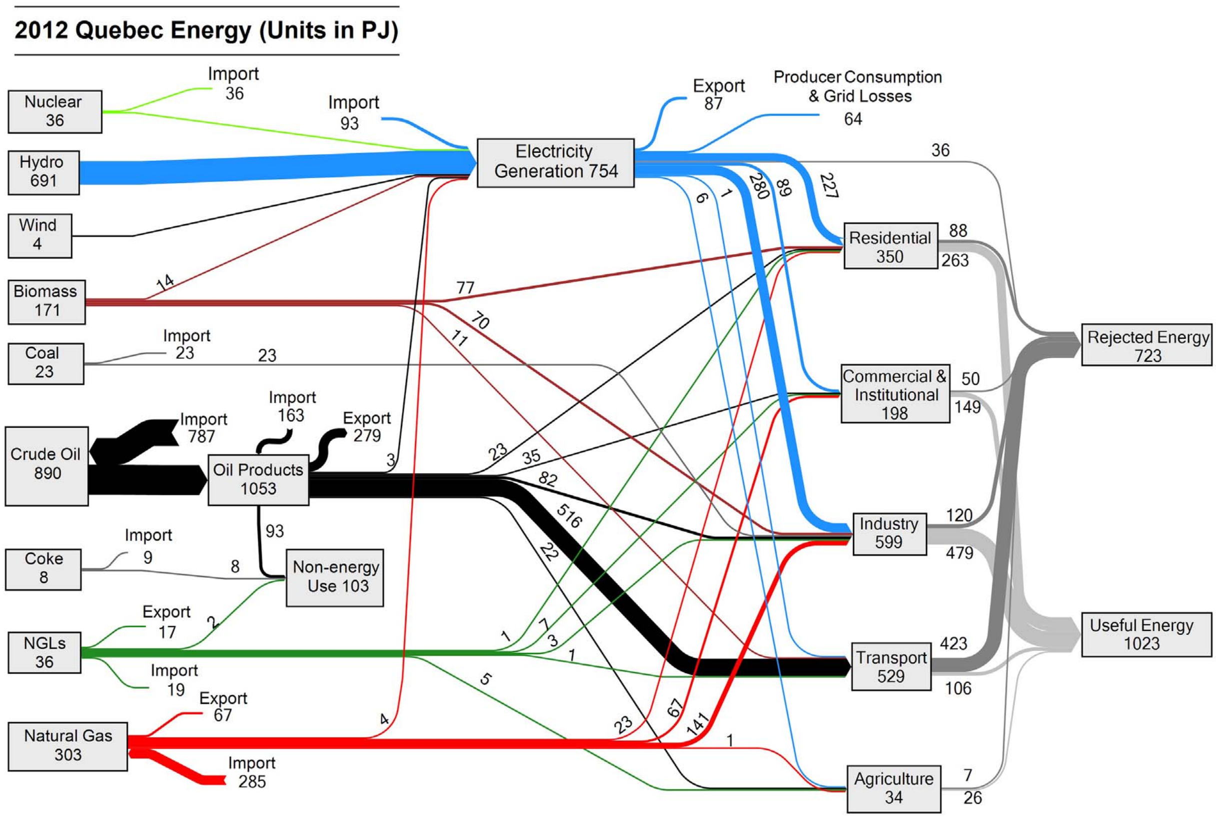

Fig. 9. Sankey diagram showing energy flow for Quebec in 2012.

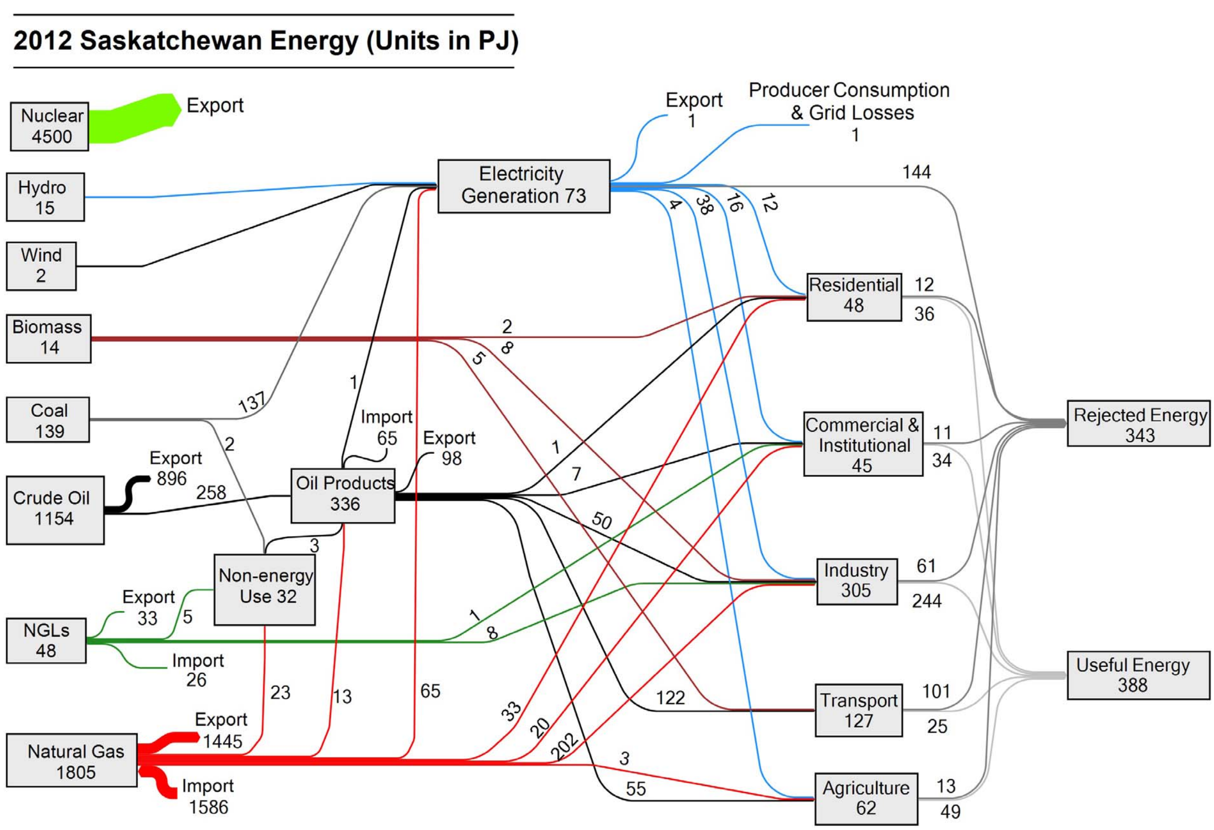

Fig. 10. Sankey diagram showing energy flow for Saskatchewan in 2012.

study year. Crude oil contributed most of the energy in the mix (43.7%) followed by hydro-electricity (28.7%), NG (12.6%), and biomass (7.1%); the remainder came from other sources (nuclear, NGLs, coal, and wind). In the electricity mix, the primary share came from hydro (81.8%) and the second largest share came from imported sources (11%). The major energy exports were oil products (279 PJ), electricity (87 PJ), and NG (67 PJ). In the demand sector, 1710 PJ of energy were consumed in 2012. Of this total, the industrial sector consumed the highest amount of energy (35%) in 2012 followed by the transport sector (30.9%), the residential sector (20.5%), the commercial and institutional sector (11.6%), and the agriculture sector (2%) [12,40–44,52]. Refined petroleum product consumption in the residential sector has fallen by 45% since 2009; however, the commercial and institutional sector increased consumption by 44% [38]. The ratio of rejected and useful energy is calculated to be 1:1.42. Total imports of energy were 1415 PJ and total exports were 449 PJ. This indicates a deficit in energy production in the province in 2012.

3.1.7. Energy flow in Saskatchewan in 2012

The total energy flow for Saskatchewan in 2012 is illustrated in Fig. 10. The total available energy in Saskatchewan's energy mix was 7742 PJ in 2012. The total electricity disposition in the province was 73 PJ; however, 77 PJ were generated from in-province generation [39,46]. This is 2.6% more than the electricity generated in 2009 [46]. Of the total energy supply, about 58% (4500 PJ) came from nuclear sources; however, no nuclear energy is consumed in the province. The remainder of energy came almost entirely from fossil fuels and a limited amount came from hydro, wind, and biomass in the study year. Other than nuclear, the highest contribution was recorded by natural gas (1805 PJ), followed by crude oil (1154 PJ), coal (139 PJ), and NGLs (48 PJ). Natural gas production in the province has decreased by 31% since 2009 [38]. In the electricity sector, the major share came from coal. Major exports came from natural gas (1445 PJ), followed by crude oil (896 PJ), NGLs (33 PJ), and some other sources, mainly electricity (1 PJ). Natural gas exports increased by 12% and crude oil exports increased by 21% between 2009 and 2012 [38]. In the demand sector, 587 PJ of energy were consumed by different economic sectors in Saskatchewan in the study year. Of the total demand, the industrial sector consumed the most energy (51.9%) in the study year followed by the transport sector (21.6%), the agriculture sector (10.6%), the residential sector (8.2%), and the commercial sector [12,40–44,52]. The industrial sector experienced a 15% increase in total energy consumption between 2009 and 2012 [38]. The ratio of rejected and useful energy is 1:1.13. Total imports of energy were 1677 PJ, and total exports were 6973 PJ. This indicates a significant surplus of energy production by the province in 2012.

3.1.8. Energy flow in the territories in 2012

The total energy flow for Northern Canada (Yukon, the Northwest Territories, and Nunavut) in 2012 is illustrated in Fig. 11. The total available energy in the Territories' energy mix was 72.7 PJ in 2012. Of the total energy available in the mix, crude oil contributed the highest amount (83.7%), followed by NG (11.1%), hydro (3.4%), NGLs (1.39%), and wind (0.01%). The total electricity generated was estimated to be 4.7 PJ [39,46]. This is 6.8% more than the electricity generated in 2009 [46]. Most of the crude oil produced (26 PJ) was exported. Total primary energy produced in the Territories has decreased by 18% since 2009 [38]. On the demand side, the total energy consumed was estimated to be 29 PJ. Of the total demand, the industrial sector consumed the highest amount of energy (44%) in the study year followed by the transport sector (22.3%), the commercial sector (20.3%), the residential sector (10.5%), and the agriculture sector (3%) [12,40–44,52]. Residential energy consumption has decreased by 19% since 2009 [38]. The ratio of rejected and useful energy is calculated to be 1:1.3. Total imports of energy were 27 PJ, whereas total exports were 38 PJ. This indicates a surplus in energy production for the territories in 2012.

3.1.9. Integrated energy flow for all provinces and territories in Canada

The total energy available in Canada's energy flow in 2012 was

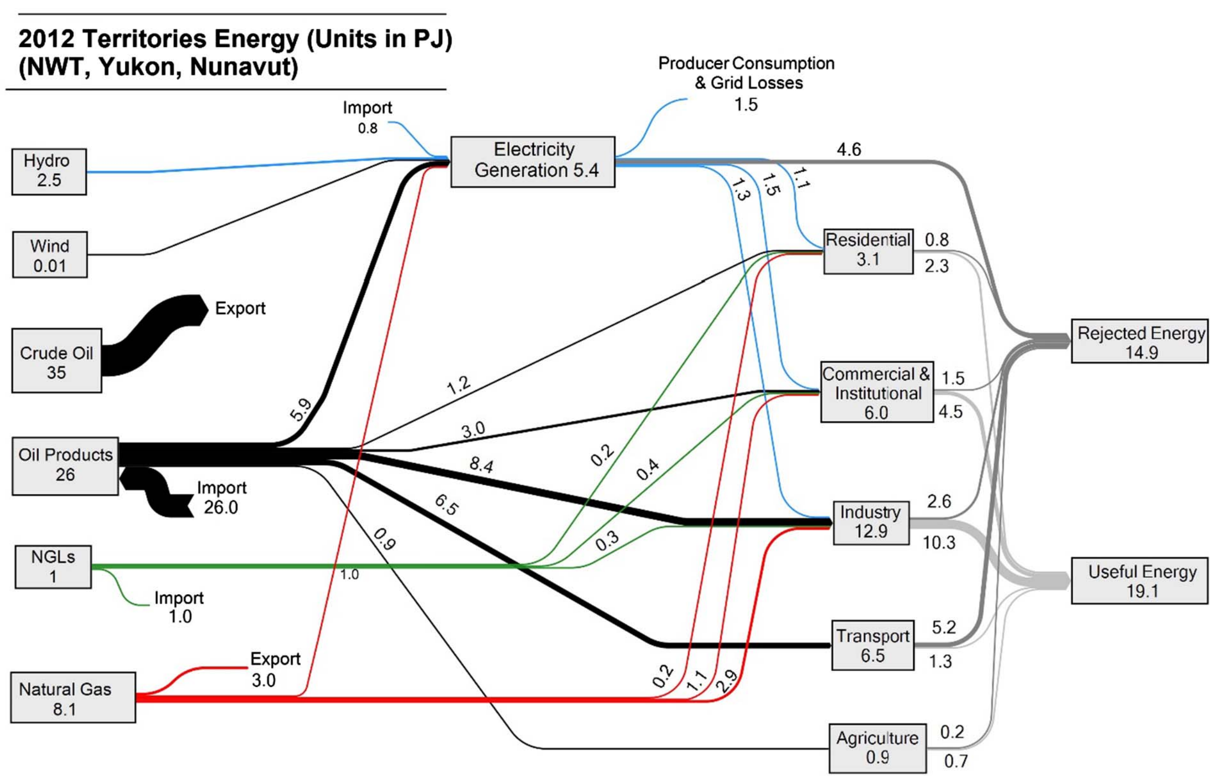

Fig. 11. Sankey diagram showing energy flow for the territories in 2012.

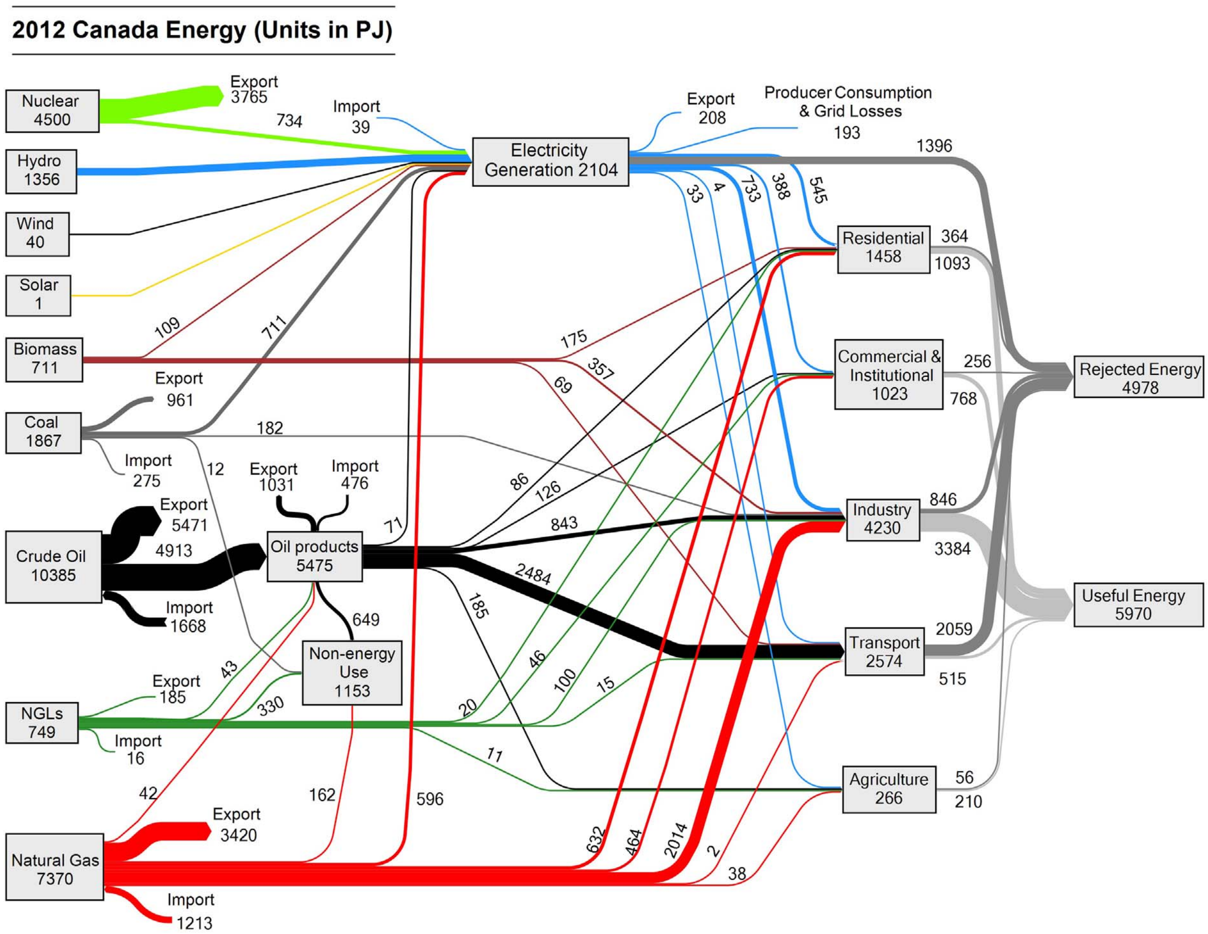

Fig. 12. Integrated energy flow Sankey diagram for Canada, 2012.

Table 5
Ranking of energy flow from primary sources to demand sectors in Canada in 2012.

Source	PJ	Proportion	End use/ consumption	PJ	Proportion
Primary source (Available energy)			**Economic sector (Final energy disposition)**		
Crude oil and oil products	10,861	39.5%	*Industry*	4,230	44.3%
Natural gas	7,370	26.8%	*Transport*	2,574	26.9%
Nuclear	4,500	16.4%	*Residential*	1,458	15.3%
Coal	1,867	6.8%	*Commercial/ institutional*	1,023	10.7%
Renewables (hydro, wind, solar)	1,397	5.1%	*Agriculture*	266	2.8%
NGLs	749	2.7%	**Sub total**	**9,552**	**34.7%**
Biomass	711	2.6%	Loss or stock change	1,746	6.4%
Electricity import	39	0.1%	Non-energy use	1,153	4.2%
Total	**27,494**	**100%**	**Export**		
			Crude oil and oil products	6,502	43.2%
Supply source			*Nuclear*	3,765	25.0%
Indigenous	23,775	86.5%	*Natural gas*	3,420	22.7%
Import	3,720	13.5%	*Coal*	962	6.4%
Total	**27,494**	**100%**	*Electricity*	208	1.4%
			NGLs	185	1.2%
			Sub total	**15,044**	**54.7%**
			Total	**27,494**	**100%**

estimated to be 27,494 PJ and is shown in Fig. 12 and Table 5. Of the total energy flow, approximately 3720 PJ were from imported sources, and the remaining 23,775 PJ were from in-country sources. Supply side energy comprises local production, imports, and stock changes, and demand side energy comprises local energy demand, exports, and non-fuel uses of energy. Canada's energy sources can be divided into two main sources, fossil fuel and non-fossil fuel. Non-fossil fuels can be divided into two main sources, renewable and nuclear. The highest amount of energy flow was observed to be 20,847 PJ (75.8%) from fossil sources followed by nuclear (4500 PJ, 16.4%) and renewable (2049 PJ, 7.7%). Most of the energy available in Canada in 2012 was from crude oil (39.9%), followed by natural gas (26.8%), nuclear (16.4%), coal (6.8%), hydro-electricity (4.9%), and others (5.2%).

Most of Canada's energy is exported. More energy (15,044 PJ) is exported than imported (3720 PJ), which clearly indicates that Canada is a net energy exporter country. The energy exported is comprised of fossil fuels, nuclear sources, and electricity. The main sources of exported energy were crude oil (5471 PJ), followed by nuclear (3765 PJ), natural gas (3420 PJ), oil products (1031 PJ), coal (961 PJ), electricity (208 PJ), and NGLs (185 PJ). Crude oil exports from Canada increased by 29% between 2009 and 2012 [38]. 2104 PJ of electricity were available in Canada in 2012. Of the total electricity supply, 2222 PJ were generated in the country [39,46]. Canada generated 3.6% more electricity in 2012 than in 2009 [46]. More than 60% of the national electricity mix came from hydro-power (1356 PJ), which makes Canada the second largest hydro-electricity producing country in the world [53].

On the demand side, 9552 PJ were consumed in Canada in 2012. Energy is supplied to the demand side as oil, natural gas, coal, NGL,

electricity, and biomass. The industrial sector consumed the highest amount of energy, 4230 PJ (44.3%), followed by the transport sector at 2574 PJ (26.9%), the residential sector at 1458 PJ (15.3%), the commercial and institutional sector at 1023 (10.7%), and the agriculture sector at 266 PJ (2.8%) [12,40–44,52]. Energy consumption by type showed that almost 97% of transportation energy came from crude oil. The industrial sector consumed mainly natural gas (47.6%), oil products (19.9%), electricity (17.3%), biomass (8.4%), and a small amount (6.7%) from other sources. The residential sector experienced a notable 25% decrease in refined petroleum product consumption between 2009 and 2012 [38].

Energy losses and useful energy consumption are also plotted on the Sankey diagrams. Most energy loss occurred in the transportation sector (80%), followed by electricity generation from thermal power plants (62.9%) (excluding the renewables, hydro-wind-solar), the commercial and institutional sector (25%), the residential sector (25%), the agriculture sector (21%), and the industrial sector (20%). The Sankey diagram illustrates that the highest energy efficiency was found in the industrial sector and the lowest in the transport sector. The overall ratio of rejected to useful energy was estimated to be 1:1.2.

A Sankey diagram of regional energy flow differences is presented in Fig. 13. The energy flows between resources and regions represent aggregated energy production and consumption. The energy flows between regions and end-use sectors include aggregated total energy consumption. Electricity generation is separated from the demand sectors for information purposes; the demand sectors include electricity use in the values. Significant energy supply is concentrated in the provinces of Alberta and Saskatchewan and accounts for 44% and 28% of Canada's total available energy, respectively. This is due to the exploitation of the abundant fossil reserves in Alberta and uranium reserves in Saskatchewan. Renewable energy is focused primarily in Quebec (865 PJ), British Columbia (400 PJ), and Ontario (281 PJ), as these regions take advantage of vast hydropower resources. Energy demands (excluding non-energy use demand) are highest in Ontario (2647 PJ), Alberta (2645 PJ), and Quebec (1710 PJ). Ontario and Quebec's high energy demand is driven by high population and GDP relative to other regions. Alberta's high energy demand is primarily due to oil sands extraction and processing in the industrial sector. Manitoba, the Atlantic provinces, and the Territories together make up only 11% of the total energy flow. This is reflected by their smaller populations and lower GDP.

4. Conclusion

Primary fuel to end use energy flows were mapped through Sankey diagrams for Canada's provinces and territories and for Canada as a whole for the year 2012. The macro view of the maps clearly shows the energy sources, energy conversion, energy consumption by economic sector, and finally useful and rejected energy. Crude oil was the dominant energy supply source (10,385 PJ) in Canada in 2012, and a major share of crude (52.7%, or 5471 PJ) was exported. Among the provinces, Alberta exported the highest amount of crude oil and oil products (5297 PJ), followed by the Atlantic provinces (963 PJ), Saskatchewan (994 PJ), Quebec (279 PJ), Manitoba (153 PJ), Ontario (87 PJ), and the territories (34.9 PJ). A significant amount of natural gas was exported by Alberta (2602 PJ), Saskatchewan (1445) and British Columbia (1011 PJ). Most of the coal stock from British Columbia (780 PJ) was exported, whereas the other provinces

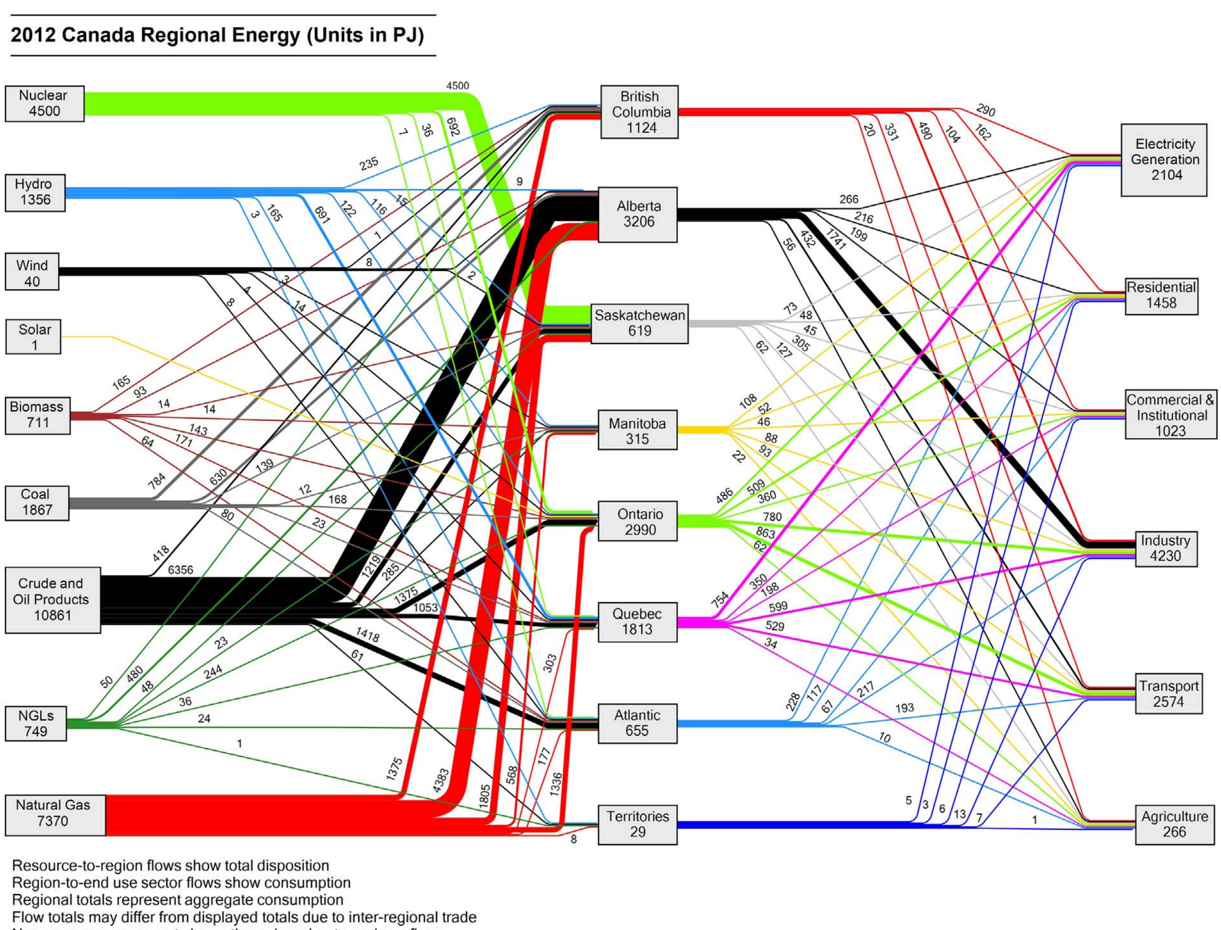

Fig. 13. Integrated regional energy Sankey diagram for Canada, 2012.

consumed nearly all of their coal. Every province exported NGLs (from 8 PJ to 163 PJ) for a total of 185 PJ. Nuclear energy was produced only in Saskatchewan (4500 PJ). All of it was exported to Ontario for processing. Ontario consumed approximately 22% of the nuclear energy it processed and exported the rest. Electricity generation was found to be mostly based on renewable energy, led by hydro-electricity (1356 PJ) and followed by biomass (109 PJ), wind (40 PJ), and a small amount of solar (1 PJ). On the demand side, the industrial sector consumed the most energy (4230 PJ) and the agriculture sector consumed the least (266 PJ) in Canada in 2012.

An analysis of the ratio of rejected to useful energy shows that the worst efficiency was observed in Ontario (1:0.93) and the Atlantic (1:0.98) and the best in BC (1:1.55); other provinces held moderate efficiencies ranging from 1:1.13 to 1:47. The overall ratio of rejected and useful energy for Canada as a whole was 1:1.2. These variations of energy efficiency can be shown in Sankey diagrams. In Ontario, about 73% of crude oil flow was consumed in the transportation sector; and in the Atlantic, about 32% of energy consumed was in the transportation sector. The transport sector has the lowest energy efficiency. On the other hand, the Quebec transport sector rejected 80% of its supplied oil products' energy (516 PJ) though its ratio of loss and useful energy was 1:1.42 due to the high amount of electricity (691 PJ, about 82%) the province produced through hydro-power, which minimized the overall loss of energy.

The maps clearly present the balance of energy flow from source to end use. The total available energy from different sources (fossils, renewables, and nuclear) is shown in the maps. There are two inflows of energy in the supply source, local production and imports. The outflows of energy from the supply source are local demand and exports. These maps can provide useful information to help understand the extent of energy consumption and the efficiency of the energy consumed in different sectors. The maps can help identify energy demand by economic sector in different forms of use. They can also help by providing information on a specific sector vulnerable to wasting energy that has the potential to improve in energy efficiency. The maps can also help formulate policy in the areas of energy conversion, refining, and end-use energy efficiency.

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